LOW-COMPLEXITY HIERARCHICAL DECODING

for

COMMUNICATIONS SYSTEMS USING

MULTIDIMENSIONAL QAM SIGNALING

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Claim To Priority Of Provisional Application

This application claims priority under 35 U.S.C. § 119(e)(1) of provisional application serial number 60/404,860, docket number TI-35080PS, filed 08/21/02, by David J. Love, Srinath Hosur and Anuj Batra.

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Background of the Invention

1. Field of the Invention

This invention relates generally to multiple-input multiple-output (MIMO)

15 communication systems. More particularly, this invention relates to a sub-optimal minimum distance (MD) decoder that outperforms known sub-optimal decoders associated with real-time systems.

2. Description of the Prior Art

20 Multiple-input multiple-output (MIMO) communication systems provide gain in capacity and quality compared to single-input single-output (SISO) communication systems. While a SISO system employs one transmitter and one receiver to receive the transmitted signal, a MIMO system in general uses $M_t >= 1$ transmitters and $M_r >= 1$ receivers. Thus the SISO system is a special case of a MIMO system, with $M_t = M_r = 1$.

25 Examples of MIMO systems include but are not limited to: 1. A communication system employing multiple-antennas at the transmitter and/or receiver; 2. A communication system employing orthogonal frequency division multiplexing (OFDM) or code division multiplexing (CDMA); 3. A time/frequency division multiple access system; 4. Any multiuser communication system; 5. Any combination of 1-4 above.

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Typically, the MIMO systems consist of a MIMO transmitter that sends "multidimensional" symbol information. This multidimensional symbol could, but is not limited to, be represented by a vector (note that a matrix symbol can always be represented as a vector symbol by stacking the columns/rows of the matrix into a vector).

5   The multidimensional symbol might represent one or more coded or uncoded data symbols corresponding to SISO transmitters. The transmitted signal propagates through the channel and is received and processed by a MIMO receiver. Note that the receiver could obtain multiple received signals corresponding to each transmitted symbol. The performance of the communication system hinges on the ability of the receiver to process

10   and find reliable estimates of the transmitted symbol based on the received signals.

Definitions

As used herein, bolded capitol symbols, such as $\mathbf{H}$, represent matrices.

As used herein, bolded lower-case symbols, such as $\mathbf{s}$, represent vectors.

15   As used herein, ^{T} denotes matrix transposition.

As used herein, $*$ denotes the matrix conjugate transpose operation.

As used herein, $^{-1}$ denotes the matrix inverse operation.

As used herein, if $\mathbf{W}$ is a matrix, $\mathbf{W}_m$ denotes the mth column of $\mathbf{W}$.

As used herein, if $\mathbf{W}$ is a matrix, $(\mathbf{W}^T)_m$ denotes the mth row of $\mathbf{W}$.

20   As used herein, if $\mathbf{v}$ is a vector, $\|v\|_2$, denotes the 2-norm of $\mathbf{v}$.

As used herein, if $Q(\cdot)$ represents the symbol slicing function, it will be assumed to slice both single symbols and multi-dimensional symbol vectors.

As used herein, I_M represents the M by M identity matrix.

As used herein, 0_{MxN} represents the M by N matrix of zeros.

25   As used herein, if A and B are sets, then $A|B$ is the set of all elements in A that are not in B.

For MIMO systems such as, but not limited to, the ones discussed herein above, the received signal can be written, after front end receive processing such as filtering,

30   downconversion, AGC, synchronization etc., in the form

$$\mathbf{y}_k = \sum_n \mathbf{H}_n \mathbf{s}_{k-n} + \mathbf{v} \tag{1}$$

where $\mathbf{H}_n$ is an M_r by M_t matrix of complex gains, $\mathbf{s}_k$ is the M_t-dimensional symbol

vector transmitted at time k, and $\mathbf{v}$ is a M_t-dimensional vector of additive noise. In

5   narrowband wireless systems where the symbol period is much larger than the RMS

delay spread as well as in OFDM systems where the inter-symbol interference is

negligible due to the insertion of a cyclic prefix and/or guard interval, the channel from

each transmit antenna to each receive antenna (per frequency bin in case of OFDM) is

often modeled as a single-tap complex gain. In this case equation (1) simplifies to

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$$\mathbf{y}_k = \mathbf{H} \mathbf{s}_k + \mathbf{v} \tag{2}$$

where $\mathbf{H}$ is now an M_r by M_t matrix of complex numbers and $\mathbf{H} \mathbf{s}_k$ is the matrix product of

$\mathbf{H}$ and $\mathbf{s}_k$.

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The receiver must estimate the symbol matrix $S=[\mathbf{s}_1 \ldots \mathbf{s}_T]$ in order to facilitate

reliable communication. Examples, but by no means the only examples, of

multidimensional symbols could be space-time codes where $T>1$ or spatial multiplexing

systems with $T=1$ and independent SISO modulation on each transmit antenna. In case of

20   no or negligible additive noise, $\mathbf{v}$, and an invertible $\mathbf{H}$, the estimation problem would

reduce to that of inverting $\mathbf{H}$. The presence of non-negligible noise, however, increases

the difficulty in estimating S. Note that we have assumed that the receiver is has some

estimate of $\mathbf{H}$, that could be obtained by transmitting appropriate training sequences. The

symbol matrix S is also assumed to be chosen from a finite set C of possible

25   multidimensional symbols (this is typically the case as for e.g. where each element of S is

chosen from a QAM symbol set).

The optimal solution in the sense of minimizing the probability of symbol error

has been shown to be the maximum aposterior (MAP) decoder which in case of

30   equiprobable symbol transmissions is equivalent to a maximum likelihood (ML) decoder.

The ML decoder attempts to find S, the symbol matrix, by using the symbol matrix $\tilde{S}$ that maximizes $p\left(\tilde{S}|y_1,....,y_T\right)$ where $p\left(\cdot \,|y_1,...., \quad y_{kT}\right)$ is the conditional probability density function (pdf) of s_k given $y_1,..., y_T$. In real-time communications systems, however, this type of decoder is overly computationally complex. Decoders that search over a set V of possible multidimensional symbols S and decode to the multidimensional symbol $\tilde{S}$ in V that minimizes some sort of metric are denoted as minimum distance (MD) decoders. The MAP and ML decoders are MD decoders with $V=C$, where C is the set of all possible multidimensional symbols S.

Many algorithms that are computationally easier than ML decoding have been proposed in order to overcome the huge computational burden of ML decodings. Algorithms that perform some form of reduced complexity decoding will be referred to herein as sub-optimal decoders. An example of a suboptimal decoder is successive interference cancellation (SIC) method. A receiver using SIC decodes each symbol within the symbol vector one at a time. After each symbol is decoded, its approximate contribution to the received vector is subtracted in order to improve the estimate of the next symbol within the symbol vector. The order of symbol decoding and subtraction could be arbitrary or based on rules such as maximization of pre/post processing SNR etc.

An example of an SIC receiver is the ordered iterative minimum mean squared error (IMMSE) receiver. With a single-tap channel, the receive signal is given by equation (2) above. Letting $s_k = [s_1\ s_2\ ...\ s_{Mr}]^T$, the ordered IMMSE operates using the following steps, letting $y_{k,0} = y_k, D_0 = \{1,2,...,M_t\}$, and $H_k^{(0)} = H$.

1. Set $m = 0$.

2. Compute $W^m = \left(H_k^{(m)*}H_k^{(m)} + \rho I_{M_t - m}\right)^{-1}H_k^{(m)*}$.

3. Let $n = \arg\min_{i\in D_0}\left\|\left(W^{(m)T}\right)_i\right\|_2$.

4. Set $\widetilde{s}_{k,n\cdot} = Q\left(\mathbf{y}_{k,m}^T \left(\mathbf{W}^{(m)T}\right)_i\right).$

5. Set $\mathbf{y}_{k,m+1} = \mathbf{y}_{k,m} - \mathbf{H}_{k,n}^{(m)}\widetilde{s}_{k,n}, D_{m+1} = D_m \setminus \{n\}$, and

$$\mathbf{H}_k^{(m+1)} = \left[\mathbf{H}_{k,1}^{(m+1)}\mathbf{H}_{k,2}^{(m+1)}\ldots\mathbf{H}_{k,n-1}^{(m+1)}\mathbf{0}_{M_r \times 1}\mathbf{H}_{k,n+1}^{(m+1)}\ldots\mathbf{H}_{k,M_l}^{(m+1)}\right].$$

6. Repeat steps 1-5 for $m < M_t$.

7. Set the decoded symbol vector to $\widetilde{\mathbf{s}}_k = \left[\widetilde{s}_{k,1} \quad \widetilde{s}_{k,2} \quad \ldots \quad \widetilde{s}_{k,M_l}\right]^T$.

Regarding the above algorithm, it is important to note that $\mathbf{H}_{k,i}^{(m+1)}$ denotes the ith row of the matrix $\mathbf{H}_k^{(m+1)}$ (time k and iteration $m+1$). Another example among sub-optimal decoders is the zero-forcing decoder which decodes to the symbol $\widetilde{s}_k = Q\left(\mathbf{H}^{-1}\mathbf{y}_k\right)$. This decoder is usually considered the worst performing and least complex of the sub-optimal decoders.

Sub-optimal techniques unfortunately differ in diversity order from ML decoding (i.e. the asymptotic slope of the average probability of bit error curve). They essentially trade reduced complexity for reduced performance.

In view of the foregoing, it is both advantageous and desirable to find other low complexity schemes with performance closer to an ML decoder, while still being low in complexity.

Summary of the Invention

The present invention is directed to a reduced search space decoding method. It provides an average probability of error performance closer to optimal decoding. The decoding algorithm provides dramatic complexity reductions as compared to optimal decoding.

According to one embodiment, a method of decoding a multidimensional symbol comprises the steps of receiving a collection of signal vectors $y_1...y_k$, with k denoting a positive integer, into a sub-optimal decoder and generating an estimated transmitted multidimensional symbol $\bar{S}$ therefrom; decoding the estimated transmitted multidimensional symbol $\bar{S}$ via hierarchical subset decoding and determining a subset therefrom; generating a reduced search space V; and decoding the received symbol vectors $y_1...y_k$ via minimum distance decoding using the reduced search space V and generating one or more of the following: an estimated multidimensional symbol $\tilde{S}$, soft bit information, or hard bit information therefrom.

Brief Description of the Drawings

Other aspects and features of the present invention and many of the attendant advantages of the present invention will be readily appreciated as the same become better

5   understood by reference to the following detailed description when considered in connection with the accompanying drawings wherein:

Figure 1 is a block diagram illustrating a hierarchical reduced search space maximum likelihood algorithm according to one embodiment of the present invention;

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Figure 2 depicts an example grouping for a 16-QAM constellation; and

Figure 3 shows the average probability of bit error for the hierarchical reduced search space maximum likelihood algorithm depicted in Figure 1 as well as ordered

15   IMMSE and ML decoder schemes when S is generated by vectors with each entry using SISO modulation.

While the above-identified drawing figures set forth particular embodiments, other embodiments of the present invention are also contemplated, as noted in the

20   discussion. In all cases, this disclosure presents illustrated embodiments of the present invention by way of representation and not limitation. Numerous other modifications and embodiments can be devised by those skilled in the art which fall within the scope and spirit of the principles of this invention.

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Detailed Description of the Preferred Embodiments

Figure 1 is a block diagram illustrating a hierarchical reduced search space

decoding method 100 according to one embodiment of the present invention. Received

5   signal vectors $y_1...y_k$ are fed into a sub-optimal decoder 102 that yields an estimate $\tilde{S}$ of

the transmitted symbol vector. One example of this would be the zero-forcing decoder

where $k=T$

$$\tilde{S} = H^{-1}[y_1...y_T].\tag{3}$$

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The estimate $\tilde{S}$ is then fed into a hierarchical subset decoding block 104. The set of N_s

possible symbol vectors is then grouped into overlapping subsets. An example of this

grouping for a system where each transmitter is using 16-QAM and $T=1$ would be to

group each dimension as shown in Figure 2 that illustrates a grouping 200 for a 16-QAM

15   constellation.

Each subset is represented by a multidimensional point c_i. A subset is chosen if

its representative point c_i minimizes $d(c_i,\tilde{S})$ where d is some sort of metric.

The subset decoder 104 is hierarchical in that it can zoom into a region. Suppose for

20   example, that each transmitter was using 64-QAM and $T=1$. This is easily seen to be 16-

QAM per quadrant. The 64-QAM constellation could be divided up similarly to that

shown in Figure 2, but with each grouping containing 16 symbol points instead of four.

After a hard decision is made upon which of the nine possible regions to search over, the

center point of the region could be subtracted from the estimated symbol and the subset

25   decoding could be repeated using the 16-QAM regions shown in Figure 2.

After a subset has been decided on, the reduced search space for that subset is created as

shown in block 106. Minimum distance decoding is then performed as shown in block

108 using the reduced search space V. This minimum distance decoding can use different

metrics for "distance" for e.g., the Euclidean distance $\|y_k - Hv\|^2$.

The inventors found method 100 to provide an average bit error rate performance between that of optimal MAP decoding and sub-optimal decoders. The method 100, while more complex than sub-optimal decoding, is many times less complex than MAP decoding.

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Any suboptimal decoder that outputs soft bit information can be combined with the hierarchical search space maximum likelihood decoding 104, as discussed herein before. The inventors simulated a MIMO system with $T=1$ with each antenna using independent 16-QAM modulation using a decoder to implement the hierarchical reduced

10   search space maximum likelihood algorithm 100 using the unordered zero-forcing decoder (i.e. channel matrix inversion). Figure 3 shows the performance of this decoder compared with ordered IMMSE and ML decoding. The hierarchical decoder was found to obtain approximately a 0.8 dB improvement at a bit error rate of 10^{-2} over ordered IMMSE decoding.

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In summary explanation, a reduced search space minimum distance decoding method provides average probability of error performance between sub-optimal decoding and MAP decoding. The decoding algorithm provides dramatic complexity reductions compared with MAP decoding.

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In view of the above, it can be seen the present invention presents a significant advancement in the art of multiple-input multiple-output (MIMO) communication systems. Further, this invention has been described in considerable detail in order to provide those skilled in the decoder art with the information needed to apply the novel

25   principles and to construct and use such specialized components as are required.

Further, in view of the foregoing descriptions, it should be apparent that the present invention represents a significant departure from the prior art in construction and operation. However, while particular embodiments of the present invention have been

30   described herein in detail, it is to be understood that various alterations, modifications

and substitutions can be made therein without departing in any way from the spirit and scope of the present invention, as defined in the claims which follow.